PCT

WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 : G01R 33/44, G01V 3/32

A1

(11) International Publication Number: WO 99/08126

(43) International Publication Date: 18 February 1999 (18.02.99)

(21) International Application Number: PCT/GB98/02398

(22) International Filing Date: 10 August 1998 (10.08.98)

(30) Priority Data:
9716993.2 11 August 1997 (11.08.97) GB

(71) Applicant (*for all designated States except US*): OXFORD INSTRUMENTS (UK) LIMITED [GB/GB]; Old Station Way, Eynsham, Witney, Oxon OX8 1TL (GB).

(72) Inventor; and
(75) Inventor/Applicant (*for US only*): SLADE, Robert, Andrew [GB/GB]; Grey Cottage, Mill Lane, Cassington, Witney, Oxon OX8 1DL (GB).

(74) Agent: GILL JENNINGS & EVERY; Broadgate House, 7 Eldon Street, London EC2M 7LH (GB).

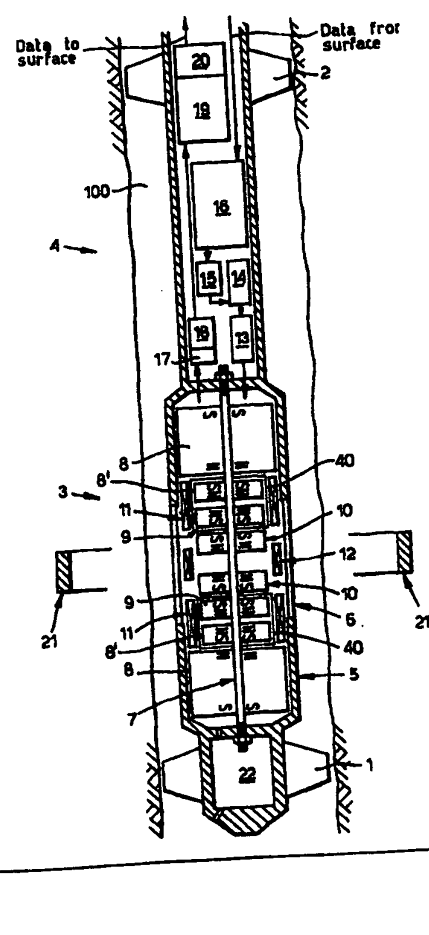
(81) Designated States: JP, US, European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

Published
With international search report.

(54) Title: MAGNETIC FIELD GENERATING ASSEMBLY FOR USE IN AN NMR APPARATUS

(57) Abstract

A magnetic field generating assembly for use in NMR apparatus. The assembly comprises one or more pairs of axially spaced, coaxially arranged main magnets (8), each pair comprising a pair of main magnets having opposite pole orientation; one or more pairs of shim magnets (8', 10) positioned between and arranged coaxially with the main magnets (8), each shim magnet having the same pole orientation as a respective nearest one of the main magnets; and one or more pairs of reversed shim magnets (9), each reversed shim magnet being positioned between and arranged coaxially with a respective main magnet and a respective shim magnet, wherein each reversed shim magnet has an opposite pole orientation to its respective main magnet and its respective shim magnet. The magnets are configured and arranged such that a working region (21) is defined radially spaced from the magnets, the magnetic field within the working region being suitable for obtaining NMR information from material in the working region.



MAGNETIC FIELD GENERATING ASSEMBLY FOR USE IN AN NMR APPARATUS

The present invention relates to a magnetic field generating assembly for use in NMR apparatus.

The Nuclear Magnetic Resonance (NMR) phenomenon has become well established in many fields as a valuable technique for the non-invasive investigation of non-metallic materials. Chemists use NMR for high-resolution spectroscopy in the field of molecular chemistry, and the technique has proved invaluable as a tool for medical diagnosis, in the guise of the MRI (Magnetic Resonance Imaging) scanner. Applications within the food and pharmaceutical industries are starting to proliferate.

In the last decade, NMR has also become firmly established as a valuable addition to the repertoire of sensor modalities available to the wireline operator, providing information about the formations that is not directly available from any other measurement.

A major factor restricting the growth of the use NMR of logging in Development wells (drilled in large numbers across an oil field already assessed to be worth commercial exploitation) has been the inherently slow logging speed of current NMR tools.

Maximum practical logging rates for current NMR tool designs are about 600 ft/hr (quite often much less, depending on the bore hole characteristics). Conventional logging tools, using different sensing modalities, such as resistivity or neutron scattering, can log at up to 1800 ft/hr. The time taken to log a well has to be accounted for when balancing the value of the information gained against the cost of logging, which is the sum of direct logging costs and the costs associated with the time lost before commercial production can start. An NMR tool which could log at a rate two or three times more than the existing systems, whilst not sacrificing quality of data, or vertical resolution (defined as the vertical extent of

borehole over which formation data is averaged), would therefore be very advantageous.

Of fundamental importance to maximum logging speed is the signal-to-noise ratio (SNR) of the NMR measurement. Unfortunately, NMR is an inherently insensitive technique and the added problems of performing NMR measurements outside the measuring apparatus, and the harsh bore hole environment, all exacerbate this problem. The designer of an NMR logging tool seeks to maximise the SNR, not only by maximising signal, but also by minimising the system noise. This is done by first removing all forms of external interference (a task aided by the bore hole environment), then by minimising all sources of thermal noise (from losses in the RF system and pre-amplifier noise, for example), until the unavoidable sample noise (from losses in the bore hole fluids) dominates.

Having taken all these precautions, the single echo, or “single shot”, SNR (defined here as the ratio of the mean amplitude of the 3rd echo in a CPMG sequence to the standard deviation in that amplitude, with a 100% water sample, under carefully defined experimental conditions) is still likely to be too low to be sufficiently accurate for reliable log interpretation. The single shot SNR for existing commercial tool designs is thought to typically range from 25:1 under optimum conditions (low sample losses, low temperature operation) to 10:1, or less, in unfavourable conditions.

NMR measurements made in bore-hole logging, such as porosity, FFI (Free Fluid Index) and BVI (Bulk Volume Irreducible) are calibrated in porosity units, or PU. 100PU corresponds to the NMR signal from a 100% liquid sample, so a porosity measurement of 20PU indicates that 20% of the sample volume is filled with sample which gives an NMR signal (ie: rock pores filled with water, oil or gas). The accuracy of the measurement is defined as the standard deviation in ±PU. The minimum acceptable level of measurement accuracy is generally taken to be ±1.5PU, but

preferably ±1PU. An accuracy of ±1.5PU corresponds to a measurement accuracy of 3 parts in 100, and ±1PU to an accuracy of 2 parts in 100. To achieve this accuracy a SNR of 33:1 is required in the former case and 50:1 in the later. If the single shot SNR is less than 33:1, as is almost always the case with down-hole NMR logging tools, then measurements, in the form of NMR pulse sequences, must be averaged to achieve this level. It is common practice to average pulse sequences in phase alternated pairs, to remove systematic errors and baseline offsets. As the tool is moving during the process of taking measurements, the data for averaged measurements is a rolling average over the bore hole strata traversed during the measurements. To maximise the resolution capability of the tool it is obviously desirable to minimise the number of averages. The single shot SNR required to meet the desired accuracy level reduces in inverse proportion to the square root of the number of averages (this relationship is due to the deterministic nature of the signal and the stochastic nature of the noise). To achieve good vertical resolution at fast logging speeds it is necessary to limit the number of averages; if four averages is chosen as a maximum limit for the preferred embodiment, to minimise the vertical resolution, then the minimum required single shot SNR reduces by a factor of two, to 16.5:1 for ±1.5PU accuracy and 25:1 for ±1PU accuracy. The designer of an NMR logging tool capable of fast logging with good vertical resolution must therefore ensure that the minimum single shot SNR under all conditions is at least 16.5:1 and preferable 25:1, or better.

It is therefore desirable to maximise signal by design. It is possible to show that received NMR signal is linearly related to the sensitive region volume, proportional to the square of magnetic field strength in that region, and proportional to the RF magnetic field strength from receiver and transmitter antennae in a complex fashion, determined by the RF coil geometry. The

designers task in maximising SNR is therefore very complex and it is a recognised necessity that a mathematical model of the tool is created to guide the optimisation. However, there are also further constraints related to the shape of the sensitive volume to be considered.

Logging is, of course, performed with the tool in constant motion up the bore hole. This results in a problem known as "outflow" which will now be described with reference to Figure 7. A tool 70 in a bore hole 71 takes a series of NMR measurements on material outside the bore hole in a cylindrical working region (or sensitive volume) 72 with axial extent L. The illustrative tool 70 has a cylindrically symmetric sensitive volume 72 but the effect of outflow is not confined to tool designs with a cylindrically symmetric sensitive volume. During the course of a typical pulse sequence of total duration typically between 0.05 and 1 seconds, the tool 70 will have moved a distance D, anything from a few millimetres to a few centimetres, depending on logging speed. A typical RF pulse sequence used in NMR measurements is a CPMG pulse sequence which consists of a 90° pulse followed by a series of 180° pulses. As the tool moves, the magnetization "tagged" by the 90° pulse moves out of the bottom of the working region 72, into a region 73 where the refocusing power of the 180° pulses fails, and signal from this region no longer contributes to the echo. The net effect is a linear attenuation of echo amplitude as the pulse sequence progresses. This is called the "outflow" effect. If D is greater than or equal to L, the echo amplitude will fall to zero before or at the end of the sequence. Therefore L >> D is a design requirement for all NMR logging tools. The tool described by Hanley, in WO92/07279, has sensitive volume with axial extent L of only 2 inches, so the maximum logging speed is 400 ft/hr (for a 20% out-flow and typical pulse sequence duration of 0.3s), which, although potentially useful, does not satisfy the requirements of a fast logging tool.

As discussed above, the shape of the working region has an important effect on the design of the NMR logging tool, and existing systems have primarily been designed with static performance in mind.

Each CPMG pulse sequence measurement must be applied to formation in which the net magnetization is at, or near, equilibrium. The formation magnetization approaches equilibrium in an exponential fashion with time constant T1, called the longitudinal relaxation time constant, or spin-lattice time constant. T1 is dependent on the formation rock properties. True equilibrium is only reached when the tool is stationary in the bore hole for several T1 periods, in which case the magnetization is defined by the B0 field:

$$\underline{M}=\frac{\chi_B \underline{B}}{\mu_0}$$

where χ_B is the material's magnetic susceptibility. This situation never occurs in the case of a moving tool, so it is accepted practice to perform the NMR measurement when the formation magnetization is near to its static-tool equilibrium value ie: it is in quasi-equilibrium, lined up predominantly radially along the B0 magnetic field in the sensitive volume and with magnitude within about ±30% of its equilibrium value. Furthermore, if the sample has previously been disturbed by measurement with an RF pulse sequence, it is normal to wait three T1 time constants for the magnetization to recover to quasi-equilibrium. If T1 is long (half a second or more) then the tool must move slowly if using this method, or the distance travelled in the bore hole will be large and the vertical resolution of four averaged measurements will be poor. When logging at the fastest speeds compatible with an acceptable "outflow" error, rather than waiting three T1 periods for the previously pulsed formation to recover, it may be

preferable to wait between measurements until the tool has moved a distance such that the sensitive volume has moved completely beyond the previously pulsed formation onto "freshly magnetised" formation. This approach, called "vertical stacking", is shown schematically in Fig. 7 (c). This method will only be preferable if the axial extent, L, of the sensitive volume is sufficiently short that the time taken to move to fresh formation is less than three T1 periods.

The designer therefore has to reconcile conflicting requirements for sensitive volume axial extent, L. It must be long enough so that the outflow condition is satisfied:

$$L >> D$$

where $D=T_{seq}*v$, v is the logging speed and T_{seq} is the duration of the pulse sequence needed to measure the desired bore hole parameters); and short enough so that the "vertical stacking" condition is satisfied:

$$L << 3*T1*v$$

Obviously, this design trade-off requires knowledge of the likely range of values of T1 in bore-holes, but this data is becoming available from laboratory measurements on rock cores.

If the method of vertical stacking is to be used successfully, it is necessary that the fresh formation used in each measurement must be sufficiently magnetised, or pre-polarised, so that when pulsed it induces a measurable voltage echo signal in the receiver system. The un-pulsed formation away from the tool's magnetic field has no net magnetization. As the tool approaches, the formation magnetization takes time to orient itself along the magnetic field of the tool, again governed by the T1 time constant of the formation rocks. A feature of the Jackson magnet system which aids full and rapid magnetization is

the strong pre-polarising field generated by the tool in the region above the toroidal sensitive volume. This field originates from the upper main magnet pole. Alongside the pole the magnetic field is much stronger than its value in the sensitive region, aiding rapid polarisation of the formation rocks passing through it. Unfortunately, in this region the field is predominantly axially oriented. However, mathematical modelling of the preferred tool embodiment shows that over a range of typical T1 values, and suitable fast logging speeds, the magnetization relaxes from an axial orientation to a predominantly radial orientation as it enters the sensitive region. Depending on T1 and logging speed, the magnitude of the magnetization in the sensitive region at the start of the measurement pulse sequence is within ±30% of its equilibrium. In fact, an increase in magnitude of 10 to 30% over the static case is seen over an optimum range of fast logging speeds. This results in a commensurate increase in single shot SNR.

A conventional magnet geometry described by Jackson in US4350955 employs a pair of axially spaced, coaxially arranged main magnets with opposite pole orientation to generate a magnetic field in a working region radially spaced from the magnets, the magnetic field within the working region being suitable for obtaining NMR information from material in the working region. The Jackson magnet geometry has been modified by providing at least one pair of shim magnets positioned between and arranged coaxially with the main magnets, each shim magnet having the same pole orientation as a respective nearest one of the main magnets, as described by Hanley in EP-A-0774671 and WO 92/07279.

If the magnetic field is calculated for a slim, 4.75" diameter, axially optimised modified Jackson system, as described in WO92/07279 using typical magnet materials, and the second order axial B_0 gradient is cancelled at a radius of 150mm by an appropriate pair of shim magnets, then a cylindrical shell is formed with centre field ~122 Gauss

(corresponding to 520 kHz, for hydrogen ions), and radial gradient ~ 8 G/cm. If the RF bandwidth is chosen to be 17kHz, (corresponding to a peak pulse power in the 10 to 20 kilowatt region, typically the maximum achievable with current, bore hole suitable, technology), then the sensitive shell will be found to have axial extent of ~30cm and thickness ~5mm. Simulation reveals that the estimated single shot SNR is less than 15:1. This system is well suited to diffusion type measurements, which take advantage of the strong radial B_0 gradient, and could also be designed as a dual frequency system, to improve the vertical resolution at higher logging speeds by hopping between two alternate resonant frequencies and two associated resonant shell radii, as described by Chandler, R. N., Drack, E. O., Miller, M. N., Prammer, M. G., Improved Log Quality with a Dual-Frequency Pulsed NMR Tool, SPE 28365, Proceedings of the 69th Annual Technical Conference and Exhibition of the Society of Petroleum Engineers, New Orleans, Sept. 1994. However it is not ideally suited to rapid well logging due to the large number of measurement averages necessary to achieve acceptable porosity accuracy.

In accordance with the present invention there is provided a magnetic field generating assembly for use in NMR apparatus, the assembly comprising one or more pairs of axially spaced, coaxially arranged main magnets, each pair comprising a pair of main magnets having opposite pole orientations; one or more pairs of shim magnets positioned between and arranged coaxially with the main magnets, each shim magnet having the same pole orientation as a respective nearest one of the main magnets; and one or more pairs of reversed shim magnets, each reversed shim magnet being positioned between and arranged coaxially with a respective main magnet and a respective shim magnet, wherein each reversed shim magnet has an opposite pole orientation to its respective main magnet and its respective shim magnet, and wherein the magnets are

configured and arranged such that a working region is defined radially spaced from the magnets, the magnetic field within the working region being suitable for obtaining NMR information from material in the working region.

The present invention provides a further modification to the Jackson magnet geometry by including an additional pair of shim magnets (the pair of reversed shim magnets) with reversed magnetic pole orientation. The reversed shims enable the magnetic profile of the assembly to be controlled more precisely than in conventional Jackson magnet arrangements. Although the reversed shims can cause a reduction of magnetic field strength in the working region when compared with conventional arrangements, it has been recognised that this potential disadvantage is more than offset by the advantages provided by the reversed shims: in particular the improved control over the shape and location of the working region and the magnetic field gradient within this working region.

For example the reversed shims can be suitably arranged such that they reduce the radial magnetic field gradient and hence increase the radial width and the total volume of the working region when compared with conventional arrangements. Of course, the Divergence Theorem must be satisfied, and this results in some increase in the axial magnetic field gradient away from the centre plane, but the overall effect can be shown to result in an increase in SNR for the same RF bandwidth.

One or more pairs of additional shim magnets may also be provided, each additional shim magnet being positioned between and arranged coaxially with a respective main magnet and a respective reversed shim magnet, wherein each additional shim magnet has the same pole orientation as its respective main magnet.

Typically the main and/or shim and/or reversed shim and/or additional shim magnets are permanent magnets, although one or more of the magnets may be electromagnets.

The reversed shim magnets (and, where provided, the additional shim magnets) are typically located in a strong opposing magnetic field, which is attempting to demagnetise the reversed shim magnets. Therefore in a preferred embodiment the reversed shim magnets (and, where provided, the additional shim magnets) are permanent magnets formed with a magnetic material having a coercivity chosen so that the working point is above the knee in the second quadrant of the materials BH curve, thus ensuring that the shim suffers no permanent de-magnetisation. This prevents the reversed shim magnets from suffering irreversible demagnetisation. In a preferred example the magnetic material comprises a rare earth alloy, such as Samarium Cobalt or Neobdinium Iron Boron.

Typically the pair of shim magnets are located in a much weaker demagnetising field, and therefore the shim magnets are advantageously ferrite magnets, which have high resistivity.

RF magnetic fields which are employed in NMR experiments can generate eddy currents in the shim or reversed shim magnets. It is not possible to simply remove the eddy currents by slotting or laminating the magnet material. This is because the laminations, which would have to be radially aligned like the spokes of a wheel, would need to be thinner than the skin depth of RF current in the magnet material. At typical resonant frequencies in the sub 1MHz region this thickness is less than a fraction of a millimetre, so this approach is impractical, particularly where the magnetic material is a rare earth (which can be brittle and hard to machine). Therefore in a preferred embodiment the assembly further comprises one or more electrically conductive sleeves (typically tubular) which each surround one or more reversed shim magnets and which are arranged to carry eddy currents in use. Where additional shim magnets are provided they are also preferably surrounded by an electrically conductive sleeve. Since eddy currents are formed in the sleeve(s), eddy

currents in the reversed shim magnet(s) are reduced, enabling the positions of the magnet(s) to be adjusted without affecting the RF fields. Preferably the or each sleeve is thicker than 5-7 skin depths. This ensures that eddy currents will flow only in the sleeve, and not in the magnet(s). Advantageously the assembly comprises a pair of electrically conductive sleeves which each surrounds a respective one of the pair of reversed shim magnets. In one example the or each sleeve is formed with silver plated copper.

The assembly may be "radially optimised" (ie. generating a radially oriented magnetic field in the working region which exhibits a saddle point in field magnitude in the working region. However preferably the assembly is "axially optimised", ie. the axial positions and strengths of the magnets are arranged such that the working region extends substantially parallel with the axis of the magnets and the radially oriented magnetic field in the working region exhibits a radial gradient which is substantially uniform in the axial direction. In the case of an "axially optimised system" the reversed shims can modify the working region (as compared to the working region of the arrangement described in EP-A-0774671) by reducing its axial length, increasing its radial width, and increasing its total volume for the same RF bandwidth. However typically the radial width of the working region is still less than the axial length of the working region.

The shim magnets and/or the reversed shim magnets and/or additional shim magnets may be relatively adjustable in the axial direction as described in WO 92/07279.

The invention also relates to NMR apparatus comprising a magnetic field generating assembly according to the present invention; an RF transmit antenna for generating an RF magnetic field within the working region and having characteristics suitable for performing an NMR experiment on material within the working region; and an RF receive

antenna for sensing an RF magnetic field generated by nuclei of the material in the working region.

Typically the RF transmit antenna and/or the RF receive antenna are positioned between the pair of main magnets. The RF magnetic field must be substantially orthogonal to the static magnetic field for NMR measurements, necessitating an axial or azimuthal orientation in the working region.

Typically the RF transmit antenna and/or the RF receive antenna comprises one or more electrical coils (which may be wound outside the shim and/or reversed shim magnets). The coils may comprise "bird-cage" or "light house" coils, but preferably comprise solenoidal coils. The axis of the or each coil is preferably parallel to the axis of the magnets to create an axial RF magnetic field.

A single coil may be used both as RF transmit antenna and RF receive antenna. However in a preferred example separate coils are employed, ie. the apparatus comprises at least one RF transmit antenna coil and at least one RF receive antenna coil, wherein the transmit antenna and receive antenna coils are electrically separate.

Preferably each coil comprises a plurality of serially connected winding elements, wherein winding elements of one coil are interleaved and substantially coaxial with winding elements of the other coil, and wherein at least one of the coils comprises one or more winding elements which are counter-wound with respect to the other winding element(s) in the coil. This arrangement results in reduced coupling between the RF transmit antenna and RF receive antenna coils, as discussed in copending British patent application GB9618267.0.

The NMR apparatus may be used for any desired purpose, but is particularly suited for use in a bore hole. According to a second aspect of the present invention a method of bore hole logging or measuring-whilst-drilling comprises moving NMR apparatus according to the first aspect of the present invention along a bore hole;

generating an RF magnetic field within the working region and having characteristics suitable for performing an NMR experiment on material within the working region; and sensing an RF magnetic field generated by nuclei of the material in the working region.

An example of a magnetic field generating assembly according to the present invention will now be described with reference to the accompanying Figures, in which:-

Figure 1 is a schematic view (not to scale) of an example of an NMR well logging tool according to the present invention carrying out a borehole measurement;

Figure 1A illustrates the dimensions of the magnet assembly;

Figure 2 illustrates the magnetic field profile generated by the magnet assembly of Figure 1A;

Figure 3 is a schematic view illustrating a typical RF coil system;

Figure 4 illustrates a suitable B_1 transmit field profile;

Figure 5 illustrates the receive field profile;

Figure 6 illustrates the electronic components housed in the electronics chassis of the apparatus illustrated in Figure 1;

Figure 7 illustrates outflow and vertical stacking; and,

Figure 8 is a schematic view of an alternative well logging tool.

Referring to the schematic view of Figure 1, a well logging tool is illustrated in a borehole 100 making a series of NMR measurements as the tool is moved along the length of the borehole 100. The tool comprises two main sections: a sensor sonde 3 and an electronics chassis 4. The sonde 3 can be filled with a suitable fluid such as oil at well pressure, and is controlled by a pressure compensation system 22.

The sonde body 5 is metallic, but must have an RF transparent centre section over the RF coils, such as a

glass fibre sleeve 6. The tensional strength of the sonde is improved by inserting a non-magnetic bar 7 through the magnets 8-10 and the RF coils 11,12 and by pre-tensioning the sonde 3. The rod 7 has little effect on the electromagnetic efficiency of the system. The tool is centralised in the borehole 100 by means of flexible centralisers 2,1 fitted at the top and bottom of the tool.

The sonde 3 contains a pair of main magnets 8 which are axially spaced, coaxially arranged and have opposite pole orientation (i.e. their north poles are facing each other). A pair of inner shim magnets 10 is positioned between and arranged coaxially with the main magnets 8, each shim magnet 10 having the same pole orientation as a respective nearest one of the main magnets 8. That is, the upper shim magnet 10 has a south pole which is facing the north pole of the upper main magnet 8, and the lower shim magnet 10 has a south pole which is facing the north pole of the lower main magnet 8. A pair of reversed shim magnets 9 is positioned between and arranged coaxially with a respective main magnet 8 and a respective shim magnet 10, and each reversed shim magnet 9 has an opposite pole orientation to its respective main magnet and its respective shim magnet.

A pair of additional shim magnets 8′ are provided, each additional shim magnet being positioned between and arranged coaxially with a respective main magnet 8 and a respective reversed shim magnet 11. The shim magnets 8′ each have the same pole orientation as their respective main magnet.

A set of RF transmit antenna and RF receive antenna coil windings are located between the main magnets 8 and are arranged as a central "field forming" solenoidal group 12 and a pair of outer "coupling control" solenoidal groups 11, described in further detail below.

The axial positions and strengths of the magnets 8-10 are chosen such that a working region 21 is defined

radially spaced from the magnets and located in the material outside the borehole 100.

The reversed shims 9 make it possible to control both the radial B_0 gradient and the axial extent of the working region 21. By judicious positioning of the shims the axial extent of the working region 21 is set to that desired for fast logging (15 cm for this geometry). Simultaneously to be sufficiently axially long to minimise outflow during the pulse sequence, but sufficiently short to retain a good vertical resolution the radial B_0 gradient is reduced so that the shell thickness is increased for the same RF bandwidth. In this way the volume of the working region 21 can be increased, although its length is reduced; hence SNR is maintained. The shorter axial length of the working region allows the RF coils to be made more efficient. The reversed shim magnets 9 unavoidably have the adverse tendency to weaken the B_0 intensity in the working region 21, but only by 10-20%.

The additional shim magnets 8′ are essentially an extension of the main magnets 8. The additional shim magnets 8′ ensure that the magnetic field is sufficiently high in the working region 21, but have a lower outer diameter than the main magnets 8 to provide space for the RF coil windings 11,12.

Figure 1A illustrates the dimensions (in mm) of the magnets 8-10 shown in Figure 1. The magnet assembly is symmetrical about centre plane 50. The magnets 8,8′,9 are formed with Sm_2Co_1 alloy and have a remanence B_r of approximately 1.12T and an intrinsic coercivity H_{CJ} of approximately 800kA/M. The magnets 10 are Ferrite, and have a remanence of approximately 0.45T and an intrinsic coercivity H_{CJ} of approximately 220kA/M.

The magnets 8-10 are each formed by unitary magnet members. However in general one or more of the magnets 8-10 may be split into two or more sub-groups.

Figure 2 shows a field plot of the B_0 field generated by the magnet geometry of the preferred tool illustrated in

Figures 1 and 1A (6" OD version). The plot is in the radial-axial plane, with the tool centre-line as the vertical axis and the centre-plane 50 (resulting from the magnet geometry) as the horizontal axis. The tool outer diameter is indicated at 116. The scale is shown, and chosen to zoom in on the working region. The data for this plot was produced using a proprietary electromagnetic finite element analysis software package (Vector Fields OPERA 2D). The arrows represent the magnetic field vectors on a grid in space across the sensitive volume. The B_0 111G contour lines are indicated at 110,111, and the B_0 115G contour lines are indicated at 112,113. The contour lines 110-113 show the bounds of the B_0 magnitude (BMOD) defined by the RF pulse centre field and bandwidth (in this case 113G, or 481kHz, and ±2G, or ±8.5kHz). The radial magnetic field gradient is ~ 4 G/cm, resulting in a shell thickness of 10mm. Obviously, the field has mirror symmetry across the centre plane.

The weakening of the radial B_0 gradient means that measurements based on the diffusion of fluids during the pulse sequence become more difficult, but not impossible. These measurements remain an option, possibly at lower logging speeds.

The long curving "tail" 114 attached to the top, and bottom, of the working region 21, and the loop shaped region, or "lobe" 115, at smaller radii than the working region 21, both represent regions with magnetic field intensity at or near resonance (resonance being defined by the frequency of the RF B_1 field generated by the RF coils 11,12). However, simulation reveals that, even in the static case, little coherent signal arises from these regions. In the region of the borehole lobe 115, the RF B_1 field is very strong and this causes multiple rotations of the magnetization during the RF pulses. The net effect is to create very small adjacent regions of alternate pole orientation signal within the lobe 115. The signal contribution from these regions tend to cancel each other

out. The great majority of signal from this region is therefore lost, which is desirable because this region lies in the borehole fluid, and offers no useful information. In the region of the "tail" 114, the B_1 field is weak and the magnetization is only rotated by small angles. Nevertheless, some signal is contributed from these regions when the tool is stationary. However, when the tool beings to move, even slowly, this signal is rapidly lost due to motion effects, predominantly outflow.

The reversed shim magnets 9 sit in a strong opposing magnetic field, which is attempting to de-magnetise them. If the shims were made from ferrite permanent magnet material, they would suffer irreversible demagnetisation. To resist this effect, a permanent magnet material with a high coercivity is required. Several rare earth magnets, such as those based on alloys of Samarium and Cobalt, and alloys of Neobdinium, Boron and Iron, have suitable properties. If such material is used for the reversed shim magnets 9, it can be shown using suitable analysis (such as electromagnetic finite element analysis) that no part of the shim will be demagnetised below its safe working point, and that no irreversible demagnetisation will occur.

The problem with the use of such material is its high electrical conductivity in comparison to ferrite. Rare earth materials can be used for the main magnets 8 and additional shims 8' because they are far enough away from the RF coils that the eddy currents induced in them by the RF magnetic fields are sufficiently small to have negligible effect on the RF losses and RF field profiles. The reversed shims 9, however, are inside the ends of the RF coil, and will therefore couple strongly to it. A method to control this effect is described in the next section. The inner shims 10 can still advantageously be ferrite, as they sit in a much weaker demagnetising field.

In the preferred embodiment described here, it is necessary to consider the effect on the RF coil design of the reversed shims 9. The reversed shims 9 and additional

shims 8′ sit inside the outermost winding banks of the Rx and Tx coils, so coupling to the coils is inevitable. Eddy currents will be induced in the outer diameter of the shim, flowing in the opposite sense to the driving coils. These eddy currents will dissipate power (hence reducing the quality factor, Q, of the RF coils), will reduce the coil's inductance, and will seriously affect the RF field profiles. It is therefore necessary to both control these eddy currents, and to take their effect into account in the RF coil design.

It is not possible to simply remove the eddy currents by slotting or laminating the shim material. This is because the laminations, which would have to be radially aligned like the spokes of a wheel, would need to be thinner than the skin depth of RF current in the shim material. This thickness is less than a fraction of a millimetre, so this approach is impractical, given the brittle, hard-to-machine nature of rare earth magnet material.

The first step is therefore to accept, and then to control, the eddy currents, disassociating them from the shim position and properties. This is done by placing each reversed shim 9 inside a high conductivity tubular shield 40, such as a silver plated copper cylinder. If the conducting tube is thicker than 5 to 7 skin depths, the eddy currents will flow only in the tube, not in the shim. The shim position can then be adjusted without affecting the RF fields. It now remains to take the effect of the eddy currents in the shim shield tube into account in the design of the RF coils. This can be achieved by a variety of methods, one technique being finite element analysis to solve Maxwell's equations, as relevant to this problem. Proprietary software is available to perform this calculation (eg: Vector Fields ELEKTRA).

The following three types of RF system may be used with the magnet assembly of Figure 1A:

1. A single axially oriented solenoid RF coil antenna, producing substantially homogeneous, axially oriented RF field across the sensitive volume, used for both receive and transmit, with an RF electronics system suitable for pulsed NMR measurements.
2. Separate axially oriented solenoid coil antennae for receive and transmit, each arranged to produce substantially homogeneous axially oriented RF fields across the sensitive volume, and with zero mutual inductance, connected to RF electronics suitable for pulsed NMR measurements.
3. Single, or separate, RF antennae arranged with axially oriented conductors, to produce substantially homogeneous, substantially azimuthally oriented RF fields across the sensitive volume, connected to RF electronics suitable for pulsed NMR measurements.

Option 2 is described in detail below.

The B_1 field across the working region needs to be substantially axially oriented and substantially uniform, in order to excite the magnetization efficiently. This can be achieved with a solenoidal RF coil, of OD ~6", wound outside the shim magnets. It is theoretically quite possible to use the same coil to receive the NMR echo signals. However, there are technical problems with this approach related to achieving minimum system dead-time. If a single coil is used for both receive and transmit functions, it is necessary to disconnect the pre-amplifier from the coil during transmit pulses, to save it from destruction by the high power pulse. It is also necessary to disconnect the transmit antenna power amplifier from the coil during receive mode, to avoid injection of noise into the receive antenna system. This function cannot be achieved with a mechanical or electronic switch without introducing extra losses and unreliability into the system.

The usual solution in conventional NMR systems is the use of a "quarter-wave line". This is a coaxial transmission cable of length one quarter of the resonant wavelength. When one end is open circuit it behaves like an almost ideal loss-less conductor to frequency components at, or near, resonance. When one end is shorted, for example by crossed diodes turned on by the application of transmit antenna power to the other end, it behaves like an open circuit.

At the low frequencies used in NMR logging tools, a cable one quarter wavelength long would be hundreds of metres long and very bulky. However, the same function can be performed by a set of lumped passive components, usually either a capacitor-inductor-capacitor or inductor-capacitor-inductor "pi network". However, these components are also bulky, hard to manufacture with ideal characteristics, and tend to store pulse energy, adding to system dead-time. In summary, the single coil approach is possible, but not favoured in the preferred embodiment, due to a variety of technical difficulties.

The favoured approach is to use separate coils for transmit and receive functions, with no galvanic connection between them. However, both coils must be axially oriented in order to produce the correct field profiles: axial B_1 in the case of the transmit coil (Tx), and sensitivity to axial fields in the case of the receive coil (Rx). In the latter case the Principle of Reciprocity dictates that the field produced by the Rx coil at each point in space defines the sensitivity of the coil to signal from that point in space. The Tx and Rx coils must therefore lie in close proximity on the same axis, and their fields will inevitably couple. However, as mentioned, there must be very little feed through of the transmit antenna power from the Tx coil to the Rx coil during RF pulses, in order to protect the sensitive Rx pre-amplifier from destruction. By the same token, the pre-amplifier must be de-coupled from the transmit antenna amplifier during reception of echoes.

Hence it is necessary to design coaxial Rx and Tx coils that produce axially oriented, and substantially uniform, magnetic field profiles in the sensitive region, but which also have almost zero mutual inductance, or coupling.

British Patent Application No. 9618267.0, describes such a system. The Tx and Rx coils are both separated into banks of serially connected co-axial windings, and these windings are interleaved. A necessary component is a reversed turn, or turns, in one of the winding banks, in one of the coils, which will generate magnetic flux in the opposite direction to the main flux from that coil. This allows the voltages induced on the various winding blocks of each coil by the field from the other coil to cancel each other, in the manner described in GB 9618267.0. If this reverse wound turn is in the Tx coil, the Gauss/amp efficiency of the coil suffers somewhat, resulting in increased power consumption, but this is unavoidable.

The coil groups 11,12 are illustrated in more detail in Figure 3 which is a schematic diagram (not to scale) in which the coil dimensions are illustrated in mm.

Figure 3 illustrates a quarter of the RF system, which is symmetrical about the centre plane 50 and tool axis 51. Each coupling control group 11 comprises a pair of receive antenna coil winding elements 101 which are positively wound, and an interleaved transmit antenna coil winding element 102 which is negatively wound (i.e. wound in the opposite direction to the winding elements 101). The field forming coil group 12 comprises three positively wound transmit antenna coil winding elements 103 and two positively wound interleaved receive antenna coil winding elements 104. Only half of the field forming coil group 12 is shown in Figure 3. The winding elements 101-104 are all substantially coaxial with the magnets 8-10. The receive antenna coil winding elements 101, 104 are serially connected and the transmit antenna coil winding elements 102,104 are serially connected and electrically separate from the receive antenna coil winding elements.

The design of the RF coils is an iterative process, moving winding bank positions and varying the number of turns in each bank, to try to meet the twin design criteria of zero-coupling and correct field profiles. The design process can be simplified by splitting the Rx and Tx winding banks into two sub-groups: a "field forming" group 12 disposed around the centre plane of the tool, and a pair of "coupling control" groups 11 at either end of the coil set, positioned over the shim shield tube 40. This is a purely a classification scheme to aid design, and does not affect the electrical connection of the winding banks. The "field forming" group 12 is sufficiently far removed from the shim shield tube 40 such that the winding bank positions can be moved without much reference to the effect of the shim tube 40, certainly for the first few iterations. The "coupling control" group 11 contains the reverse wound bank; its prime function is to have equal and opposite mutual inductance to that of the field forming group. The field intensity from these coils is reduced at the radius of the sensitive volume by the presence of the shim shield tube 40. Furthermore the coupling setting coils 11 are more remote from the working region 21 due to their axial position, so their field contribution is further reduced. It is therefore possible to optimise the mutual inductance of this group, incorporating the shim tube eddy currents, and so zero the Tx to Rx coupling, without affecting the field in the sensitive volume significantly. In this way, it is possible to iteratively optimise the RF coil design and to meet the twin field profile for the preferred tool design, utilising separate RF axially oriented solenoidal coils, as described in copending British Patent Application No. 9618267.0 and zero-coupling design requirement.

The RF field profiles for the 6" tool design illustrated in Figure 1 to 3 are shown in Figures 4 and 5. Figure 4 illustrates the B_1 transmit field profile for a nominal RF pulse with 1 A/mm^2 current density. B_1 contours

are indicated at 117 (0.4G) and at 118,119 (0.7G), and the vectors represent B_1 orientation and magnitude. Figure 5 illustrates the receive field profile - by reciprocity this is given by the field generated by the receive antenna coil with 1 A/mm^2 current density. Contours are indicated at 120, 121 (0.4G) and at 122 (0.7G). The RF coils are advantageously constructed using Litz wire for low AC losses, reducing Tx power and Rx thermal noise.

Referring to Figure 1, the electronics chassis 4 is a series of pressure vessels containing the down-hole electronics system. The electronics system is illustrated in more detail in Figure 6.

The receiver coil, 25 (Figure 6, formed by winding elements 101, 104 in coil blocks 11 and 12, as shown in Figures 1 and 3) is tuned to the resonant frequency of the sensitive shell, f_0, by means of a low loss tuning capacitor, 17. This capacitor is advantageously connected in parallel with the receiver coil so that the resultant tank circuit, 26, presents a high impedance at resonance, thereby amplifying the small voltages induced on the receive coil by the precessing nuclear magnetisation by the quality factor of the receiver tank circuit.

Similarly, the transmitter coil, 23, (Figure 6, formed by winding elements 102, 103, in coil blocks 11 and 12, as shown in Figures 1 and 3) is tuned to the resonant frequency of the sensitive shell by means of another low loss tuning capacitor, 13. Series or parallel connection of the transmit coil and capacitor are possible, to suit the output impedance characteristics of the power amplifier. However, it is convenient to connect the transmit coil and tuning capacitor in series, as shown in Figure 6. Such a connection presents a very low impedance to the driving power amplifier at resonance; this in turn allows a simple and efficient switch-mode resonant inverter to be used as the power amplifier, 14, connected directly to the transmitter tank circuit, 24. A power amplifier of this type is described in WO97/13159.

In this way, the use of separate coils for receive and transmit functions allows the receiver and transmitter electronics systems to be independently optimised, without the need for the complex coil matching systems and transmit/receive switches, or quarter-wave lines, which are used in many conventional systems. However, it will be clear to those skilled in the art that there are many other alternative ways to connect the receiver and transmitter coils to suitable electronics, including the use of alternative RF coil geometries, such as a single coil for both receive and transmit, and RF coils with axially oriented winding elements producing an azimuthally oriented RF field in the sensitive volume.

The magnet system defines the resonant frequency and has the strongest effect on signal strength, NMR signal being roughly proportional to the square of resonant frequency. However, optimization of the measurement SNR for a given magnet system is controlled by the quality factors achieved for transmitter and receiver tank circuits. The quality factor is inversely related to the tank circuit losses:

$$Q=\frac{\omega L}{R} \qquad (1)$$

where ω is the angular resonant frequency, L is the coil inductance and R the total loss resistance. Loss resistance is the sum of losses in the coil, losses in the tuning capacitor (collectively called "internal losses") and reflected losses arising from eddy currents in the conductive bore-hole fluid ("external" or "sample losses"). For SNR to the optimised, it is important to minimise the internal losses of both transmit and receive tank circuits so that the sample loss dominates. This is achieved by careful RF coil and capacitor construction, and using Litz wire to wind the RF coils, hence minimising skin and proximity effects.

Having achieved a situation where sample loss is the dominant mechanism in both transmitter and receiver tank circuits, it is clear from reference to equation 1 that the quality factors will be maximised. The quality factors effectively define the useful bandwidths of the two RF systems. The bandwidth of the transmitter system, BW_{Tx}, is inversely proportional to the RF pulse duration:

$$BW_{Tx} \propto \frac{1}{P_{180}} \qquad (2)$$

where P_{180} is the duration of the 180 degree pulse in the CPMG sequence.

In order to maximise NMR signal, the volume of excited magnetization emitting coherent signal must be maximised. Reference to equation 2 shows that the excitation bandwidth is maximised by using RF pulses which are as short as possible (in practice limited by the RF peak pulse power capability of the transmitter hardware). The radial magnetic field gradient and the excitation bandwidth define the radial thickness of the sensitive shell. As the radial gradient is predominantly linear, the excited volume, and hence NMR signal, is linearly proportional to excitation bandwidth. (The high quality factor of the transmitter tank circuit can cause the pulse rise time to be long, but this problem can be overcome by "over driving" the tank circuit at the start of the pulse, a method commonly used in low frequency NMR systems, and described in the prior art).

The natural bandwidth of the receiver tank circuit, BW_{Rx}, is defined by its quality factor:

$$BW_{Rx} = \frac{f_0}{Q_{Rx}} \qquad (4)$$

where f_0 is the resonant frequency. However, the system noise is determined by:

$$\overline{V_{noise}}=\sqrt{4kTR_{Rx}BW_{Rx}} \qquad (5)$$

where k is Boltzmann's constant and T is the system temperature.

Combining equations 1, 4 into 5:

$$\overline{V_{noise}}=\sqrt{4kT\omega L\frac{BW_{Rx}^2}{f_0}} \qquad (6)$$

it is shown that system noise is linearly proportional to receiver bandwidth. Therefore in order to optimise SNR, the bandwidth of the receiver system should be the same as that of the transmitter system, so that all of the signal from the excited volume is collected, whilst rejecting noise contributions from outside the excited frequency band.

In practice, the receiver natural bandwidth tends to be narrower than the transmitter system bandwidth, due to the lower losses associated with the low voltage receiver tank circuit. It is therefore necessary to reduce the effective quality factor of the receiver system to match the transmitter and receiver bandwidths, but without adding significant noise. This can be accomplished by connecting the receiver tank circuit to a "damped" pre-amplifier, 18. This is a circuit, commonly used in MRI systems and well documented in prior art, which acts as a low noise pre-amplifier, but has a resistive input impedance, of value chosen such that, when connected across the receiver tank circuit, it reduces the receiver quality factor by the desired amount, (thereby "damping" the tank circuit). The input impedance of the pre-amplifier is created by a feed-

back technique and is designed to be primarily real (ie: resistive) across the desired system bandwidth. It is equivalent to connecting a resistor cooled to only a few Kelvin across the tank circuit, and hence adds negligible noise. In this way the receiver system bandwidth is matched to the transmitter system bandwidth, and SNR is maximised.

A further benefit of the damped pre-amplifier is that it reduces the time taken for the receiver system to recover from over-load and transient excitation by the RF pulse, hence reducing system "dead-time" (the time after the application of an RF pulse before the system is ready to record an NMR echo signal). It is important that dead-time is minimised by careful design, so that short inter-echo pulse sequences are possible, enabling measurement of short T2 components. In practical systems, dead-time is governed by magneto-acoustic effects (vibration of the tool structure in response to the RF pulse), which are minimised by careful design, considering and controlling the vibration modes of the structure.

The remaining electronics systems necessary to perform an NMR measurement down-hole are: a specialised voltage regulator circuit, 15, at the input of the switch-mode resonant inverter power amplifier described above, to ensure that all the 180° refocussing pulses of the CPMG sequence are the same amplitude, (such a regulator circuit is described in copending British Patent Application No. 9616499.1); a bank of DC capacitors acting as an energy storage device, 16, feeding power to the voltage regulator, and thereby allowing the average RF power output during the pulse sequence to exceed the input DC power arriving from the surface; a digital spectrometer, 19, to gate on and off the power amplifier forming RF pulses at intervals as required by the CPMG sequence experiment; the spectrometer also contains circuitry to synchronously detect, or directly digitise, the echo information from the preamplifier, forming quadrature NMR signals, in a manner familiar to those skilled in the art. Preferably, the

spectrometer forms part of the down-hole tool, and exchanges information and control signals with the surface controller by means of a suitable telemetry system, 20, usually a serial digital communications link, but it could be located on the surface.

The preferred tool embodiment described has the following predicted performance:

Tool OD:	6 inches
Sensitive shell ID:	13 inches
Penetration depth in an 8" bore-hole:	2.5 inches
Single shot SNR in typical conditions:	25.4:1
Single shot SNR in lossy conditions:	17.6:1
Optimum logging speed for T1 = 1 second:	1300 ft/hr
Vertical resolution at this logging speed in typical conditions (two averages, vertically stacked):	9.5 inches
Vertical resolution at this logging speed in lossy conditions (four averages, vertically stacked):	17.3 inches
Measurement accuracy in both cases:	less than ±1.4 PU

The preferred embodiment described is for a standard well logging tool, but it can be seen that the invention could be adapted for use as a Measurement-Whilst-Drilling system.

Figure 8 is a schematic view of an alternative well logging tool. The tool is identical to the tool of Figure 1 (corresponding reference numerals being given) except that the magnetic field generating assembly does not include the additional pair of shims 8'.

CLAIMS

1. A magnetic field generating assembly for use in NMR apparatus, the assembly comprising one or more pairs of axially spaced, coaxially arranged main magnets, each pair comprising a pair of main magnets having opposite pole orientation; one or more pairs of shim magnets positioned between and arranged coaxially with the main magnets, each shim magnet having the same pole orientation as a respective nearest one of the main magnets; and one or more pairs of reversed shim magnets, each reversed shim magnet being positioned between and arranged coaxially with a respective main magnet and a respective shim magnet, wherein each reversed shim magnet has an opposite pole orientation to its respective main magnet and its respective shim magnet, and wherein the magnets are configured and arranged such that a working region is defined radially spaced from the magnets, the magnetic field within the working region being suitable for obtaining NMR information from material in the working region.

2. An assembly according to claim 1 further comprising one or more pairs of additional shim magnets, each additional shim magnet being positioned between and arranged coaxially with a respective main magnet and a respective reversed shim magnet, wherein each additional shim magnet has the same pole orientation as its respective main magnet.

3. An assembly according to claim 1 or 2 wherein the main and/or shim and/or reversed shim magnets and/or additional shim magnets are permanent magnets.

4. An assembly according to any of the preceding claims wherein the reversed shim magnets and/or additional shim magnets are permanent magnets formed with a magnetic material having a coercivity chosen so that the working point is above the knee in the second quadrant of the materials BH curve.

5. An assembly according to claim 4 wherein the reversed shim magnets and/or additional shim magnets are formed with a magnetic material comprising a rare earth alloy.

6. An assembly according to claim 5 wherein the alloy comprises Samarium Cobalt, or Neobdinium Iron Boron.

7. An assembly according to any of the preceding claims wherein the shim magnets are ferrite magnets.

8. An assembly according to any one of the preceding claims further comprising one or more electrically conductive sleeves which each surrounds a reversed shim magnet and which are arranged to carry eddy currents in use.

9. An assembly according to claim 8 comprising a pair of electrically conductive sleeves which each surrounds a respective one of the reversed shim magnets.

10. An assembly according to claim 8 or 9 wherein the sleeves are formed with silver plated copper.

11. An assembly according to any of the preceding claims wherein the magnets are configured and arranged such that the working region extends substantially parallel with the axis of the magnets and the radially oriented magnetic field in the working region exhibits a radial gradient which is substantially uniform in the axial direction.

12. An assembly according to any of the preceding claims wherein the radial width of the working region is less than the axial length of the working region.

13. An assembly according to any of the preceding claims wherein the shim magnets and/or the reversed shim magnets and/or the additional shim magnets are relatively adjustable in the axial direction.

14. An assembly according to any of the preceding claims wherein the shim magnets and/or reversed shim magnets and/or additional shim magnets have a smaller outer radius than the main magnets.

15. NMR apparatus comprising a magnetic field generating assembly according to any of the preceding claims; an RF transmit antenna for generating an RF magnetic field within

the working region and having characteristics suitable for performing an NMR experiment on material within the working region; and an RF receive antenna for sensing an RF magnetic field generated by nuclei of the material in the working region.

16. Apparatus according to claim 15 wherein the RF transmit antenna and/or the RF receive antenna are positioned between the pair of main magnets.

17. Apparatus according to claim 15 or 16 wherein the RF transmit antenna and/or the RF receive antenna comprise one or more electrical coils.

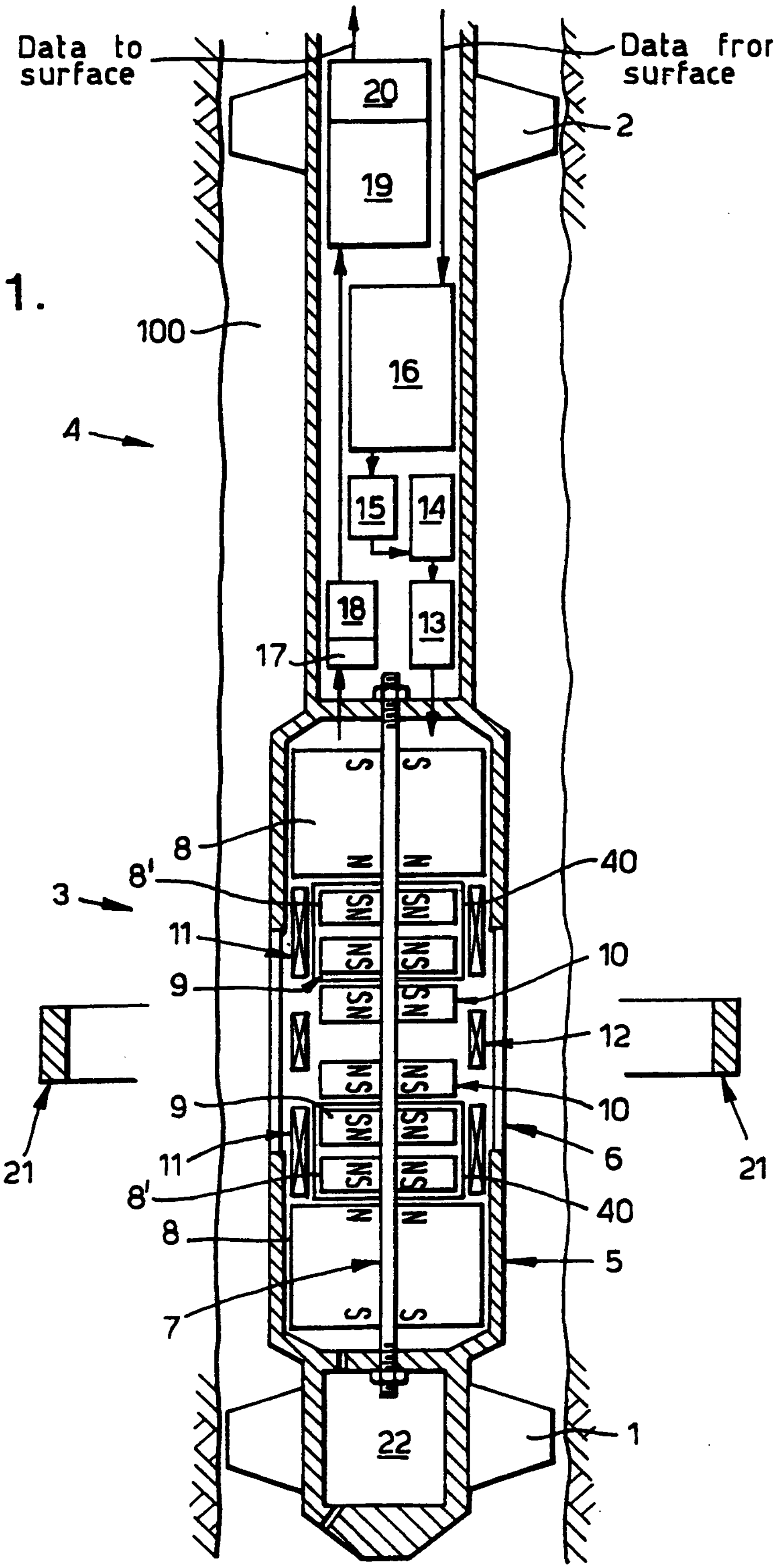
18. Apparatus according to claim 17 wherein the axis of the or each coil is parallel to the axis of the magnets.

19. Apparatus according to any of claims 17 or 18 wherein the coil(s) are wound outside the shim and/or the reversed shim magnets.

20. Apparatus according to any of claims 15 to 19, adapted for use in a bore hole.

21. A method of bore hole logging or measuring-whilst-drilling, the method comprising moving NMR apparatus according to any of claims 15 to 20 along a bore hole; generating an RF magnetic field within the working region and having characteristics suitable for performing an NMR experiment on material within the working region; and sensing an RF magnetic field generated by nuclei of the material in the working region.

Fig.1.


Data to surface
Data fror surface
20
19
2
16
100
4
15
14
18
13
17
S
S
8
N
N
40
8'
3
SN
SN
11
10
9
12
21
9
10
6
11
21
8'
40
8
5
7
22
1

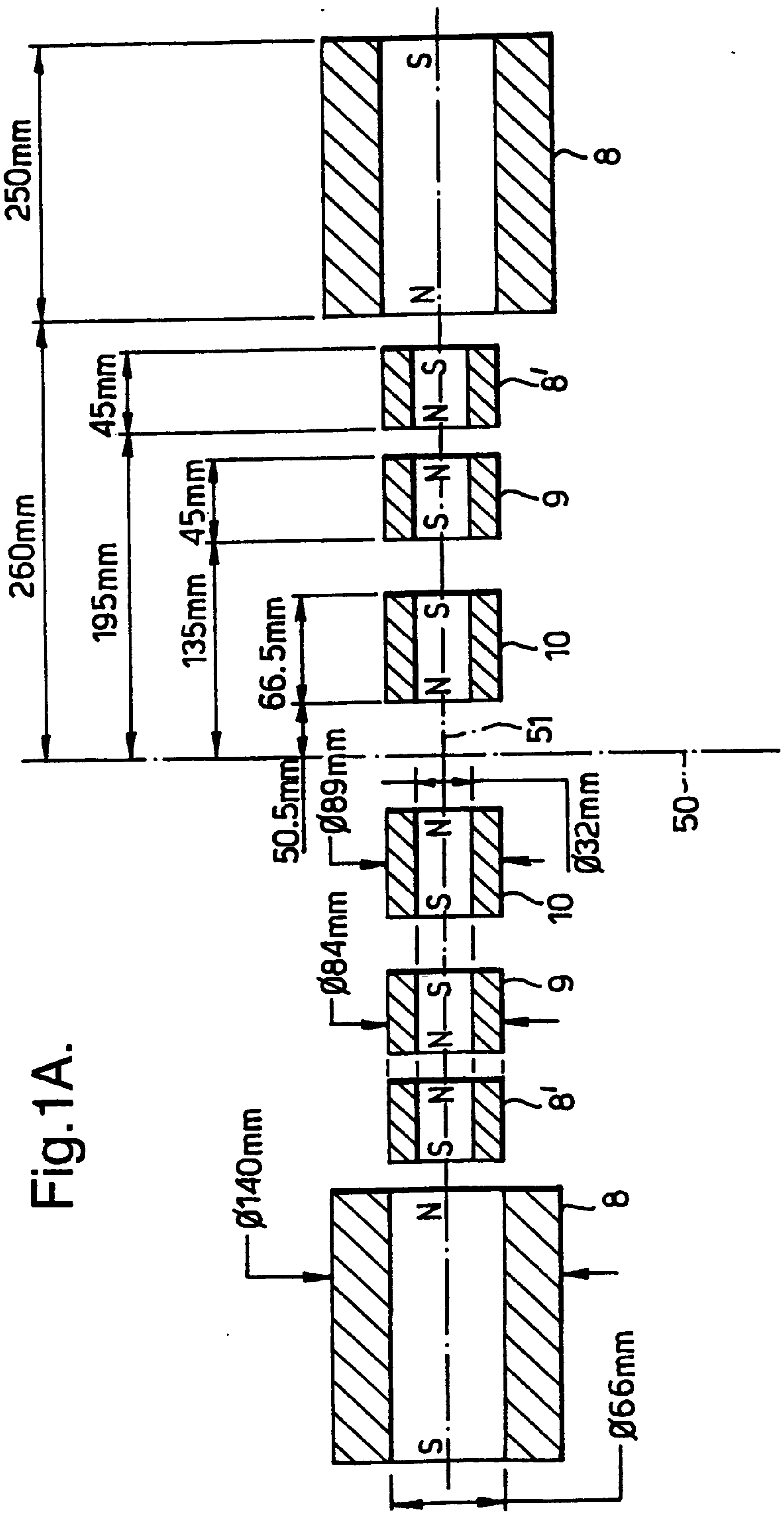
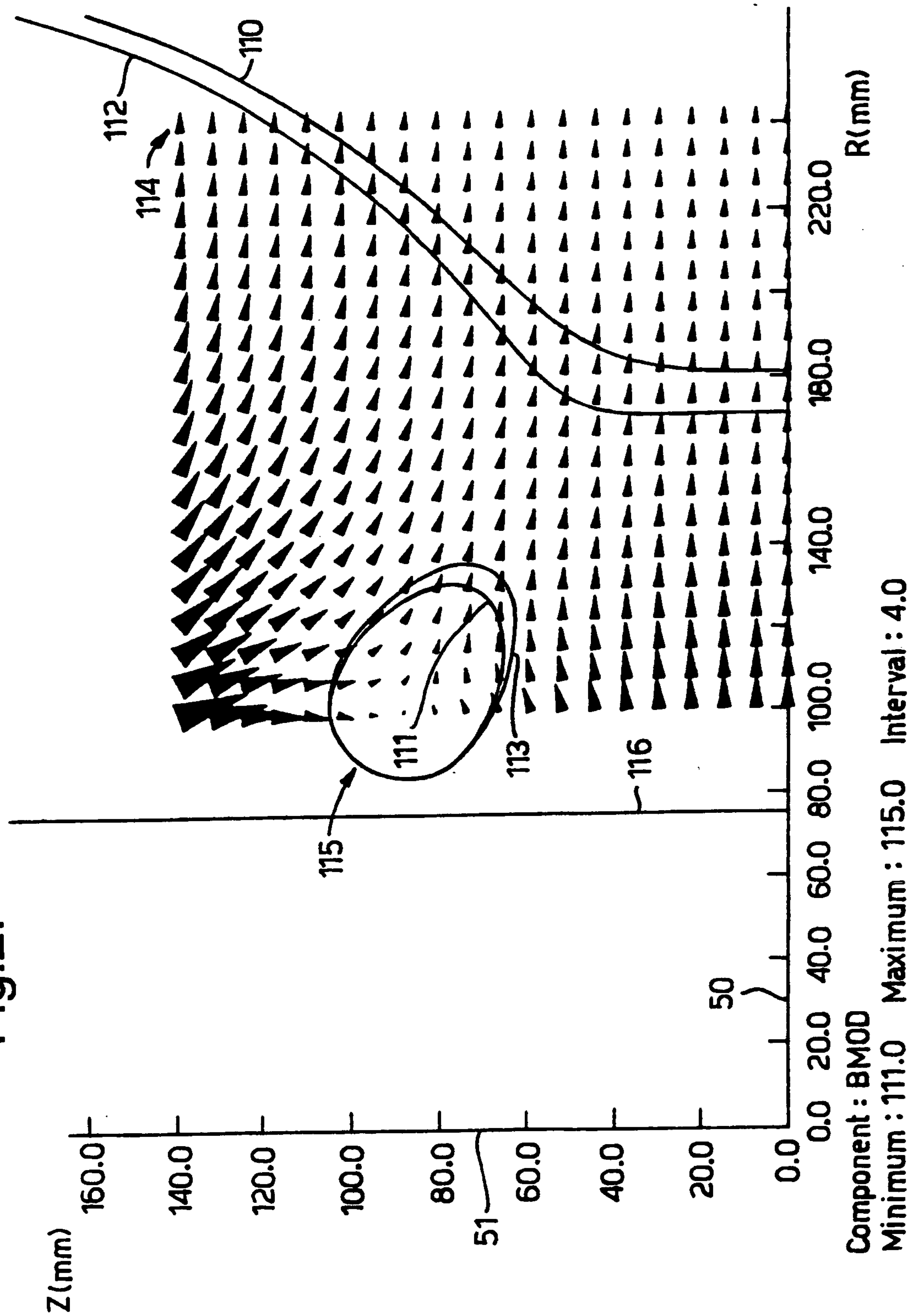

250mm
260mm
195mm
135mm
45mm
45mm
66.5mm
50.5mm
Ø89mm
Ø32mm
Ø84mm
Ø140mm
Ø66mm
S
N
8
8'
9
10
51
50

Fig.1A.

Fig.2.


Z(mm)
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
R(mm)
0.0
20.0
40.0
60.0
80.0
100.0
140.0
180.0
220.0
110
111
112
113
114
115
116
50
51
Component : BMOD
Minimum : 111.0 Maximum : 115.0 Interval : 4.0

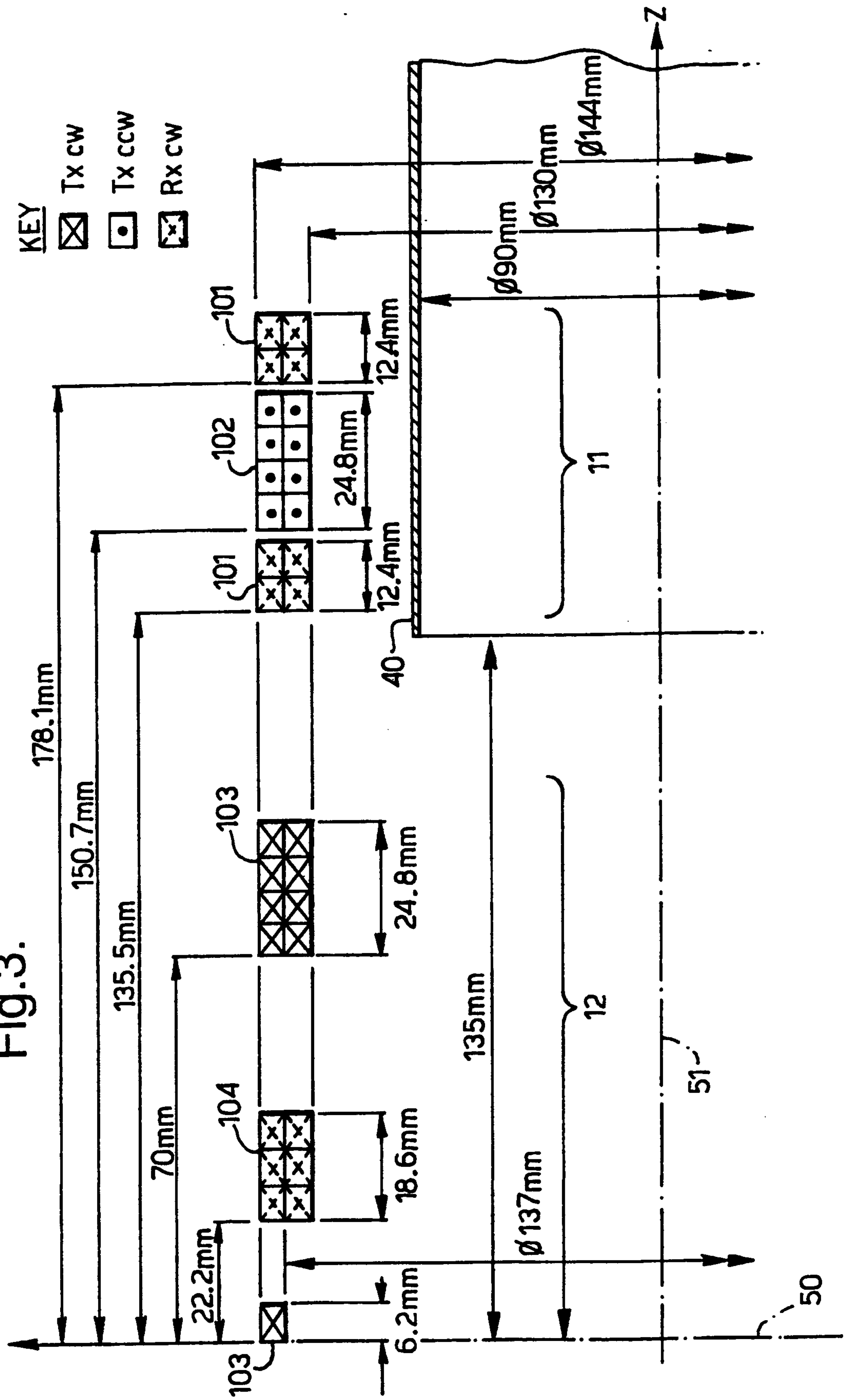

KEY
Tx cw
Tx ccw
Rx cw
Z
Ø144mm
Ø130mm
Ø90mm
Ø137mm
101
102
103
104
40
11
12
50
51
12.4mm
24.8mm
12.4mm
24.8mm
18.6mm
6.2mm
22.2mm
70mm
135.5mm
150.7mm
178.1mm
135mm

Fig.3.

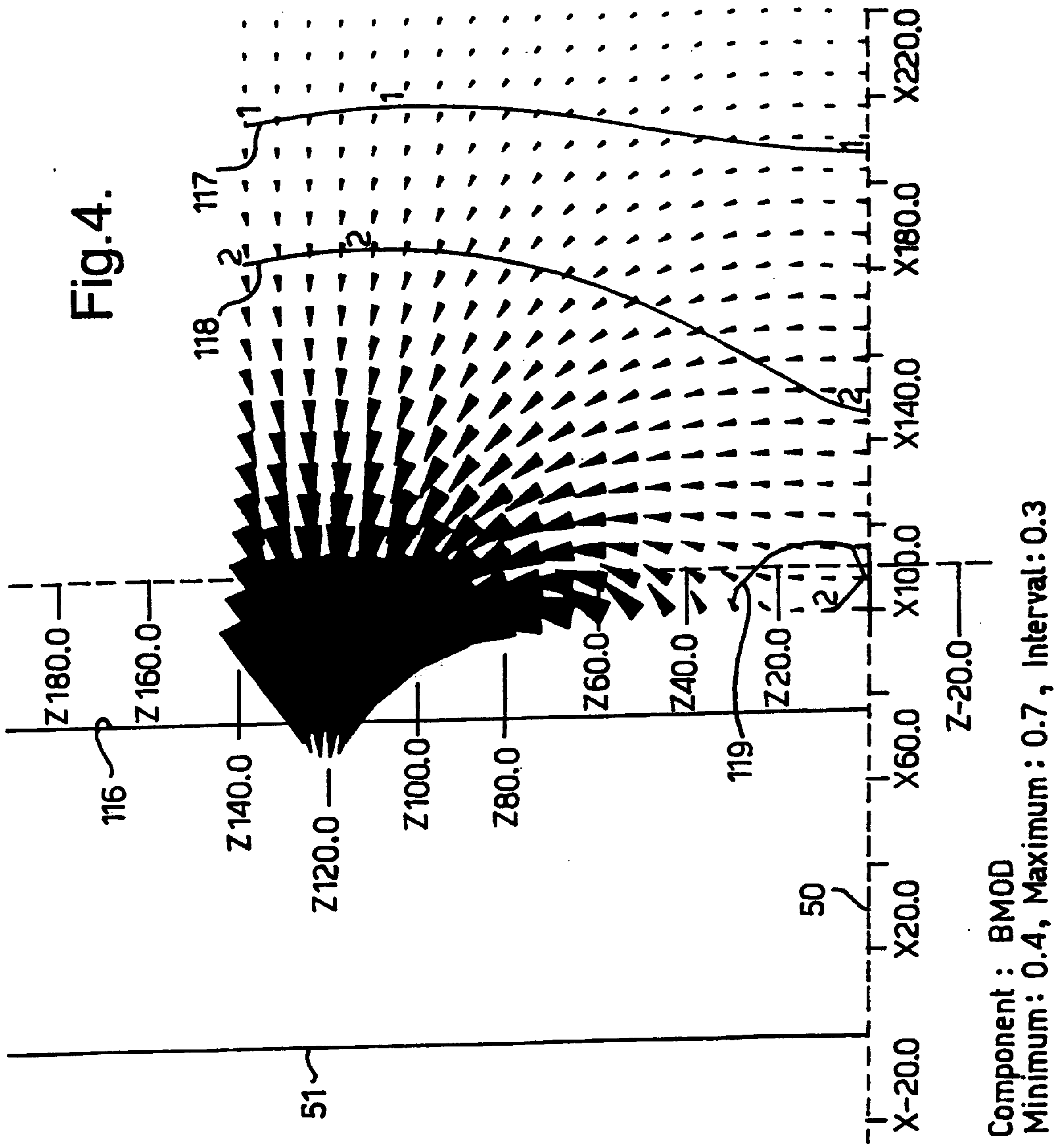
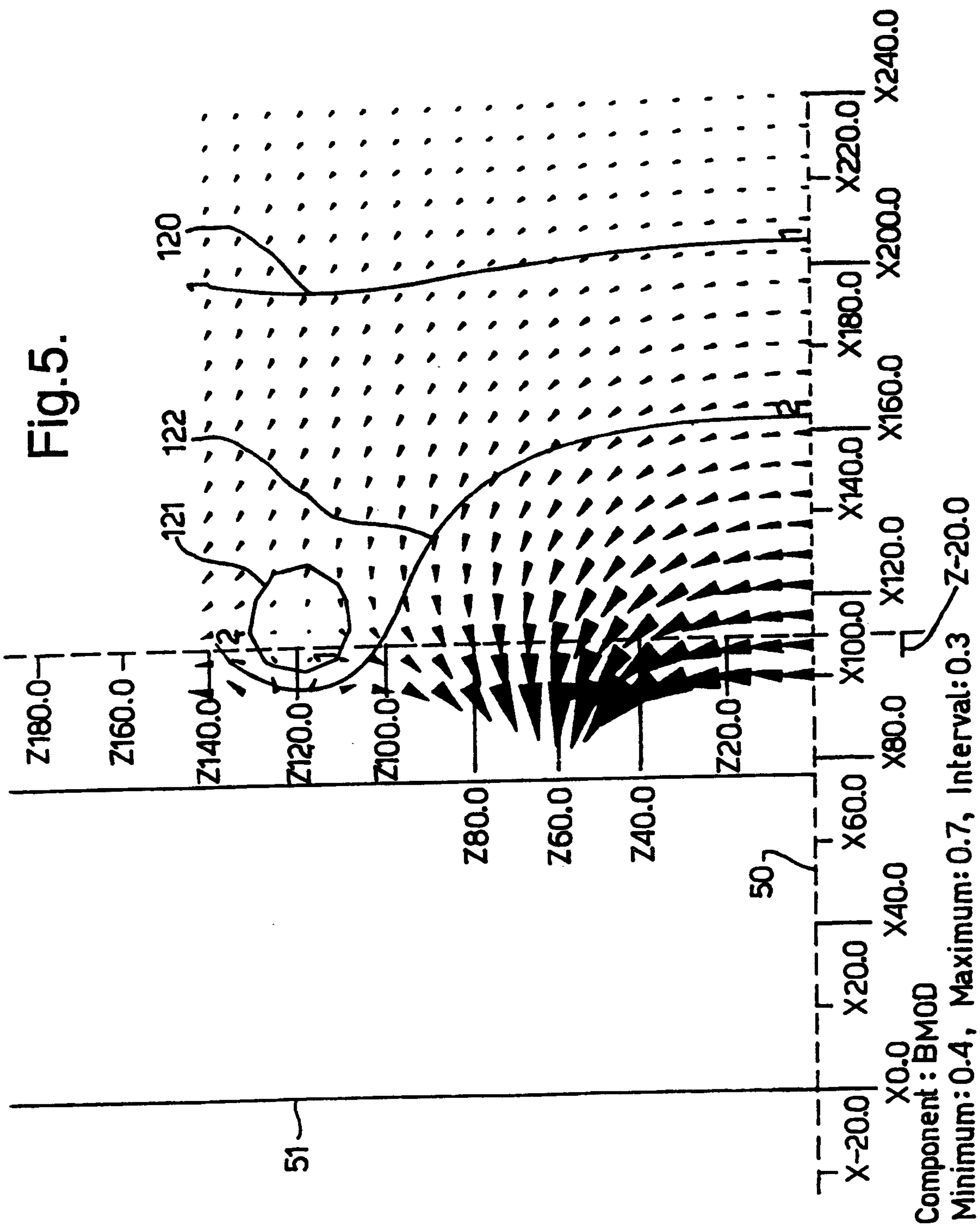

Z180.0
Z160.0
Z140.0
Z120.0
Z100.0
Z80.0
Z60.0
Z40.0
Z20.0
Z-20.0
X-20.0
X20.0
X60.0
X100.0
X140.0
X180.0
X220.0
116
117
118
119
50
51
Component : BMOD
Minimum : 0.4, Maximum : 0.7, Interval : 0.3

Fig.4.

Fig.5.


120
122
121
Z180.0
Z160.0
Z140.0
Z120.0
Z100.0
Z80.0
Z60.0
Z40.0
Z20.0
Z-20.0
X-20.0
X0.0
X20.0
X40.0
X60.0
X80.0
X100.0
X120.0
X140.0
X160.0
X180.0
X200.0
X220.0
X240.0
50
51
Component : BMOD
Minimum: 0.4, Maximum: 0.7, Interval: 0.3

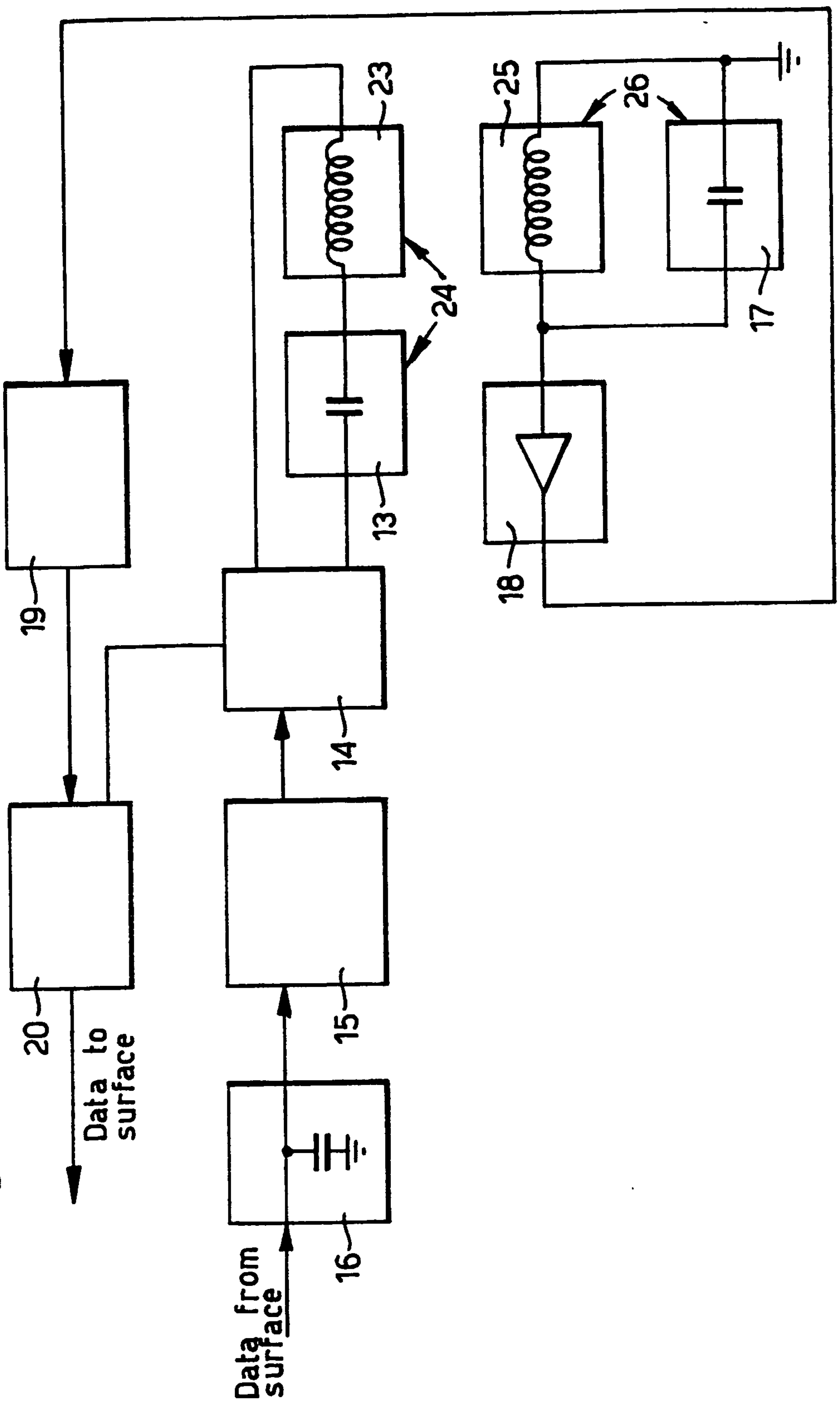

23
25
26
24
17
13
18
19
14
15
20
16
Data to surface
Data from surface

Fig.6.

Fig.7A.

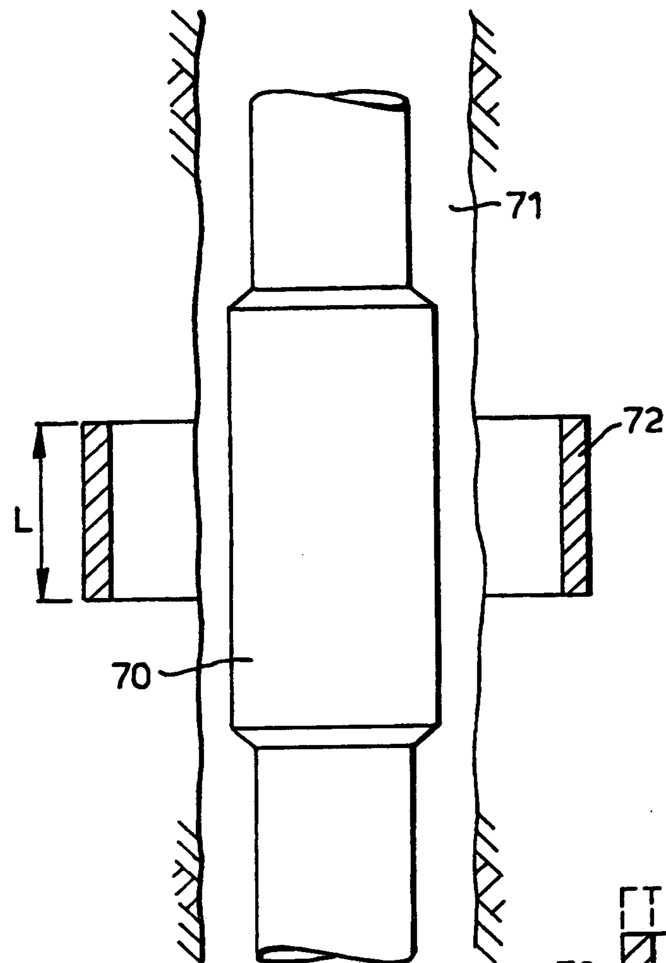


Fig.7B.

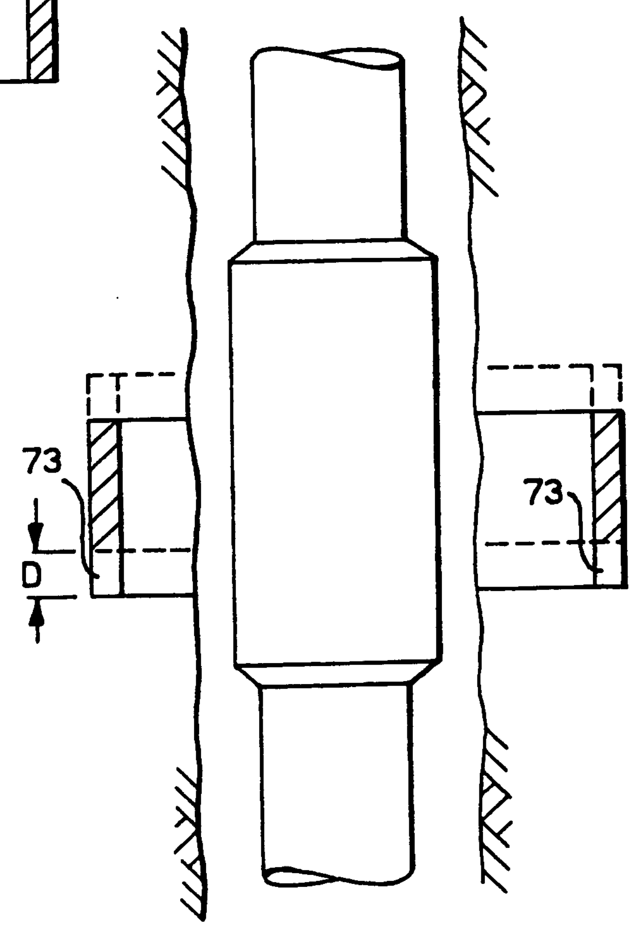
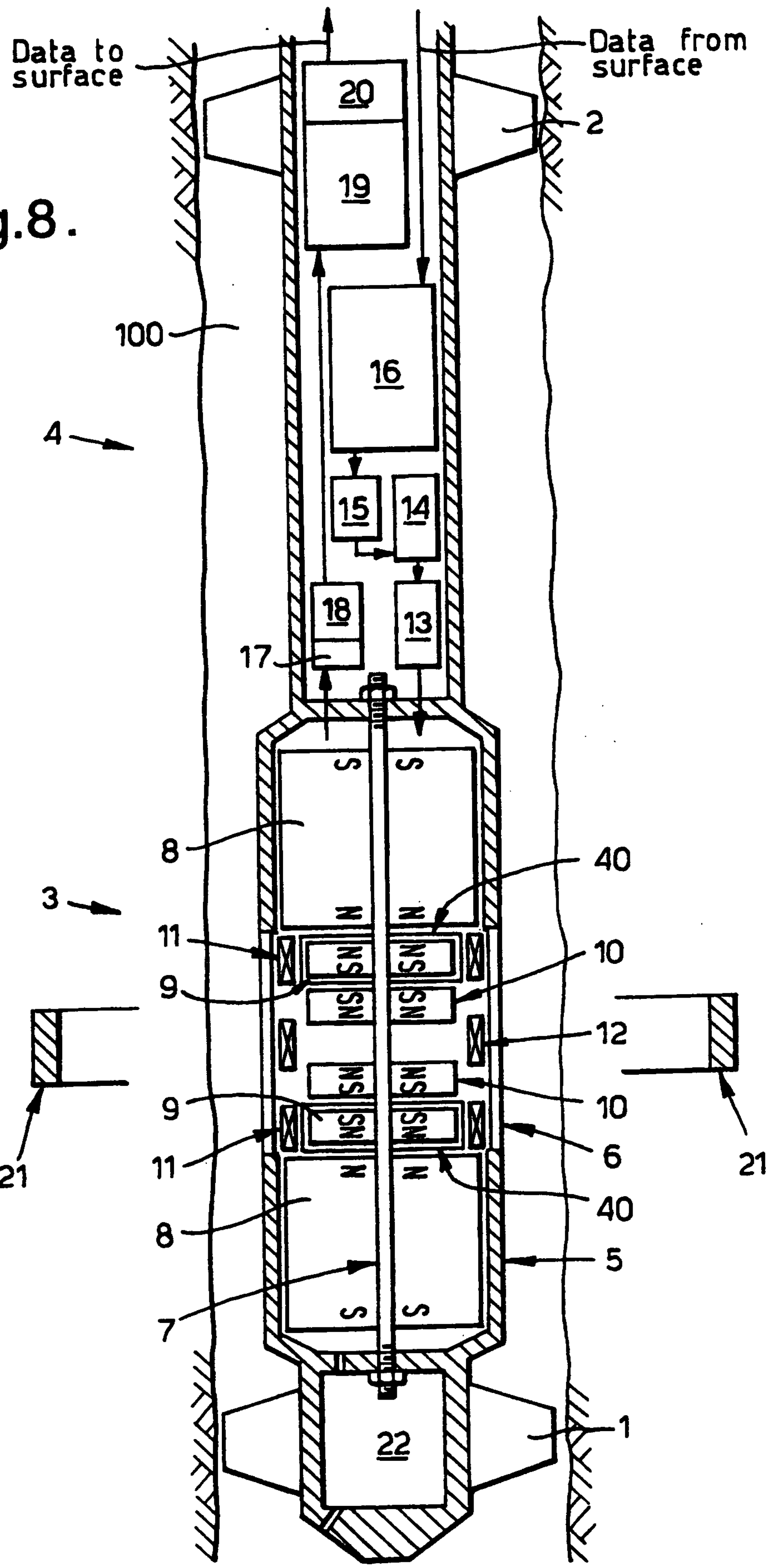


Fig.8.


Data to surface
Data from surface
20
19
2
100
16
4
15
14
18
13
17
S S
8
40
3
N N
11
10
9
12
21
21
6
40
8
5
7
22
1

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 98/02398

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G01R33/44 G01V3/32

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 G01R G01V

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 92 07279 A (OXFORD INSTR LTD) 30 April 1992 cited in the application see page 1, line 17 - page 2, line 5 see page 2, line 23 - page 7, line 25 see page 12, line 4 - page 14A, line 13; figures 1-3	1-7, 11-21
A	WO 94 18682 A (OXFORD INSTR UK LTD ;BEASLEY PAUL (GB); HANLEY PETER (GB)) 18 August 1994 see page 1, line 3 - page 5, line 2; figure 2	2-6

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
30 October 1998	09/11/1998

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Lersch, W

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/GB 98/02398

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 9207279 A	30-04-1992	DE 69125497 D	07-05-1997
		DE 69125497 T	23-10-1997
		EP 0552268 A	28-07-1993
		JP 6503884 T	28-04-1994
		US 5471140 A	28-11-1995
WO 9418682 A	18-08-1994	NONE	